Biological Effects of Radio-Frequency/Microwave Radiation

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Invited Paper

***Abstract*—Over the past 50 years, significant advances have been made in the characterization of radio-frequency/microwave (RF/MW) fields (3 kHz–300 GHz) and energy absorption, as well as in the quantification of biological responses of organisms exposed to this kind of electromagnetic energy. The known biological effects and hazards have been demonstrated to be largely thermal in nature. This paper reviews key developments in experimental and theoretical dosimetry, as well as confirmed biological effects that have formed the basis of ever more sophisticated human-exposure standards generated through the IEEE consensus process. It also suggests some potential benefits to mankind of systems based on the thermogenic character of RF/MW energy absorption.**

***Index Terms*—Comfort heating of humans, RF/microwave biological effects, RF/microwave exposure, RF/microwave safety, safety standards, specific absorption rate.**

I. INTRODUCTION

THE study of the biological effects associated with exposure to electromagnetic energy at radio-frequency/microwave (RF/MW) frequencies is a mature scientific discipline. At present, there are well over 15 000 papers in the scientific literature that report the results of laboratory studies of exposed animals, humans, *in vitro* preparations, and other relevant studies. As can be imagined, the quality of the studies is uneven, ranging from poor and incomplete to excellent. The expert panels of international standards committees, such as the IEEE International Committee on Electromagnetic Safety (ICES), critically evaluate this evolving literature on a continual basis, deliberate, and make recommendations regarding the possible impact on human health. This paper describes the important biological effects—separating confirmed and understood effects and interaction mechanisms from those that are speculative and unconfirmed—and describes how this information is used by the standards community and expert panels to develop safety criteria for human exposure.

II. CHARACTERISTICS OF BIOLOGICAL TISSUE AND ABSORPTION CHARACTERISTICS

The complex permittivity (ε) of a biological tissue is given by

$$\varepsilon = \varepsilon_r \varepsilon_0 + j\frac{\sigma}{\omega}$$

where $\varepsilon_0 = 8.86 \times 10^{-12}$ f/m, and σ is the conductivity. The relative dielectric constant (ε_r) and conductivity of various tissues have been tabulated by Durney [1] and Gabriel *et al.* [2]–[4].[1] The penetration depth δ, i.e., the distance from the boundary of a medium to the point at which the field strengths or induced current densities have been reduced to $1/e$ of their initial boundary value in the medium, is given by (1) as follows for a plane-wave incident on a planar surface:

$$\delta = \frac{1}{\omega}\left[\left(\frac{\mu_0\varepsilon_r\varepsilon_0}{2}\right)\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2}-1\right)\right]^{-1/2}. \quad (1)$$

Table I shows the approximate dielectric parameters and penetration depth for a number of frequencies for muscle tissue (tissues with high water content) [5].

As seen in this table, the penetration depth at low frequencies is large and decreases rapidly to 1 mm or less at millimeter-wave frequencies. Although the penetration depth estimated from (1) is large at lower frequencies, the amount of energy that actually penetrates a conducting body the size of a human is small because of the shunting of the electric field. At 60 Hz, for example, the internal E-field in a small spherical object is nearly six orders of magnitude less than the external E-field [6]. Only around the "resonance" frequency of man, i.e., around 40–80 MHz, is the internal E-field deep in the body within one order of magnitude of the external field [7].

The amount and distribution of the energy absorbed in a biological object exposed to RF energy is related to the internal E- and B-fields. As the incident wave penetrates a biological object, the fields interact at the various tissue interfaces resulting in a complex distribution of the local fields. These internal fields are related to a number of parameters including frequency, dielectric properties of the tissues, geometry and orientation of the

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[1] [Online]. Available: http://www.fcc.gov/fcc-bin/dielec.sh, http://www.brooks.af.mil/AFRL/HED/hedr/reports/dielectric/home.html

TABLE I
DIELECTRIC PARAMETERS FOR MUSCLE TISSUE AT VARIOUS FREQUENCIES

Frequency (MHz)	**Relative Dielectric Constant (ε_r)**	**Conductivity (σ) (S/m)**	**Penetration Depth (δ) (cm)**
0.1	1850	0.56	213
1.0	411	0.59	70
10	131	0.68	13.2
100	79	0.81	7.7
1000	60	1.33	3.4
10,000	42	13.3	0.27
100,000	8	60	0.03

* Muscle-like tissue, field parallel to tissue fibers [4].

object with respect to the incident field vectors, and whether the exposure is in the near or far field of the source. The resulting distribution of energy can be described in terms of the specific absorption rate (SAR), which is defined as the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given density (ρ) [8], i.e.,

$$\mathrm{SAR} = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) \text{ W/kg.} \tag{2}$$

The SAR is related to the internal E-field by

$$\mathrm{SAR} = \frac{\sigma |E|^2}{\rho} \text{ W/kg} \tag{3}$$

where σ is the conductivity of the tissue in siemens per meter, ρ is the mass density in kg/m^3 and E is the rms electric field strength in volts per meter. The concept of SAR is meaningful only in the frequency range between approximately 100 kHz and 6–10 GHz, i.e., where the penetration depth is of the order of 1 cm or more. Induced current density is the important parameter at RF frequencies below approximately 100 kHz; at frequencies above approximately 6–10 GHz, the energy is absorbed superficially and incident power density is important.

There is an extensive literature on the evaluation of whole-body-averaged SAR and SAR distributions for various models of animals, including man. Many of the earlier evaluations are based on simple spherical and ellipsoidal models, e.g., Durney [1], but more recent studies use numerical simulations of anatomically correct models of adult humans. The results of these studies show that near resonance ($\approx$70–80 MHz for "standard man," about half that frequency when standing on a conducting ground plane, and about 100 MHz when seated) the SAR is greatest when the incident E-field is aligned with the major axis of the body (called E-polarization—see Fig. 1). For E-polarization, a low-Q resonance is observed when the major axis of the object is approximately 0.4λ [9], where λ is the wavelength. The SAR at resonance is equal to about 0.2 W/kg per mW/cm^2 of incident power density. At higher frequencies, the SAR decreases to an asymptotic "quasi-optical" value 5–6 times lower than the SAR peak. At very low frequencies, the SAR varies as f^2, as expected. As seen in Fig. 1, the resonance is far less pronounced for H- and K-polarization. At resonance, small animals are more efficient absorbers than man, e.g., the SAR for a mouse at resonance (approximately 2 GHz), the peak SAR is somewhat over 1.0 W/kg per mW/cm^2.

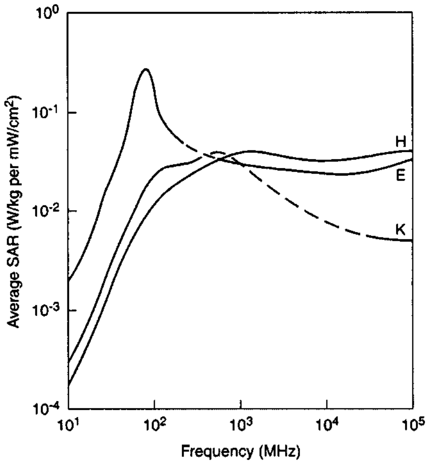

Fig. 1. Calculated whole-body average SAR versus frequency for models of the average man for three standard polarizations. The incident power density is 1 mW/cm^2. E-, H- and K-polarization refer to the component of the incident wave that is aligned with the major axis of the body (K is the wave vector) (from Durney *et al.* [1]).

SAR is a key concept in planning and analysis of experiments, both *in vivo* and *in vitro*, and serves as the basis of contemporary RF/MW safety standards for human exposure. Both whole-body average SAR and the local peak spatial-average SAR are important.

III. BIOLOGICAL EFFECTS

The goal of much research into the biological consequences of exposure to RF/MW energy is the understanding of how such exposure may compromise the normal biological functioning of *human beings*. Since many experimental maneuvers cannot be performed on human subjects, studies of animal subjects must often be substituted. Most studies that report biological effects have involved acute (minutes to hours) RF/MW exposures of animal subjects or *in vitro* preparations. Due to economic and technical concerns, only a few studies have investigated the consequences of long-term exposure of animals to controlled RF/MW fields. Almost without exception, several recently published long-term studies, e.g., Frei *et al.* [10] and [11], Toler *et* *al.* [12], Chou *et al.* [13], and Mason *et al.* [14], have failed to demonstrate any deleterious effects, including cancer, on the exposed animal subjects. A study by Repacholi *et al.* [15] indicated increased malignant tumors in transgenic mice exposed to fields characteristic of mobile phones. A replication study using a different exposure system has been completed [16], but the results are not yet available.

Over 20 recent epidemiological studies of humans chronically exposed to assorted RF/MW sources (radar, mobile phones, etc.) have suffered from multiple technical deficiencies, especially an absence of exposure assessment and, thus, have had limited utility. Many of these studies targeted cancer as an endpoint and, at best, the findings were equivocal or contradictory. The low quantum energy of RF/MW fields would not be expected to initiate or promote carcinogenesis, at least in terms of classical physical principles. In general, only a few frequencies have been studied, usually one at a time with limited field intensities. The worst case is believed to involve exposure at the resonant frequency, where the longest body dimension is 0.4λ and the RF/MW energy penetrates maximally.

IV. KNOWN/UNDERSTOOD EFFECTS (TISSUE HEATING)

A. Physiological Effects

Tissue heating is an important effect of RF/MW exposure of biological organisms that has been unequivocally demonstrated. Most of the published physiological research has concerned thermoregulatory mechanisms that quantify the ability of an organism to regulate its body temperature. These studies have been conducted primarily on laboratory animals, with a heavy emphasis on small rodents, e.g., mice, rats, and hamsters. Small mammals are poor models for human beings; their large surface-to-volume ratio requires a high metabolic heat production to maintain thermal balance in the cold. However, such animals are at a disadvantage in warm environments because they lack efficient mechanisms for heat loss. Basic information about the thermoregulatory capabilities of animal models relative to human beings is essential to the appropriate evaluation and extrapolation of animal data to man. In general, reliance on data collected on humans and nonhuman primates, however fragmentary, yield a more accurate understanding of how RF/MW fields interact with biological systems, knowledge that will best serve the needs of setting human exposure standards.

Voluminous laboratory data, collected on rhesus and squirrel monkeys (cf. Adair [17]), have demonstrated that the autonomic responses of heat production and heat loss will be mobilized efficiently when these animals undergo specific RF/MW exposures in controlled thermal environments. For example, the metabolic heat production M of endothermic mammals equilibrated to cold environments will be elevated by an amount that is directly proportional to the ambient temperature. During acute exposure of the whole body to RF/MW fields, the elevated M of nonhuman primates in the cold is reduced by an amount proportional to the field strength or SAR (Candas *et al.* [18], Lotz and Saxton [19], [20], Adair *et al.* [21], and Lotz [22]). As a result of this response adjustment, the internal body temperature is usually regulated within the limits normal for the species. In addition, heat-loss responses of vasodilation and sweating are initiated by RF/MW exposure of nonhuman primates in thermoneutral and warm environments. In each case, the magnitude of the physiological response is a direct function of the whole-body SAR [18]–[21], [23], [24].

These studies of nonhuman primates have stimulated recent research on human volunteers exposed to assorted RF/MW fields. A series of experiments has been published by Adair *et al.* [25]–[29] that are designed to obtain accurate knowledge of human thermoregulatory efficiency in RF/MW environments. A standard protocol, in which adult human volunteers undergo 45-min partial-body exposures following a 30-min equilibration to a controlled thermal environment, is always followed. These studies have involved frequencies of 450 MHz [continuous wave (CW)] and 2450 MHz (CW and pulsed) and three ambient temperatures ($T_a = 24\,^\circ\mathrm{C}, 28\,^\circ\mathrm{C}$, and $31\,^\circ\mathrm{C}$). Local peak power density was set to yield the same local peak SAR (watts per kilogram) at both frequencies. To date, 15.4 W/kg has been the maximal peak surface SAR explored (Adair *et al.* [29]), a level nearly double that specified in the 1999 edition of IEEE Standard C95.1-1991 [30] for human partial-body exposure at 2450 MHz. Each study, regardless of specific variables explored, has reported that partial-body exposures of humans, at levels at or above the maximum permissible exposure (MPE) values of the standard, are mildly thermogenic and are counteracted efficiently by normal physiological heat loss responses, principally sweating. In particular, no increase in core temperature (measured in the esophagus at the level of the heart) has ever occurred in any subject under any condition tested. The most recent study in this series involved whole-body far-field exposure at 100 MHz. Subjects reported no sensations of warmth, even at field strengths eight times the MPE values of the 1999 edition of the IEEE Standard C95.1-1991 [30], yet heat-loss responses of vasodilation and sweating maintained the body's thermal equilibrium. (It should be noted that for most of the MW range, there is perceptible sensation of warmth at reasonably low levels, but these sensations seem to fade at the lower frequencies, e.g., 50–100 MHz, where the energy is penetrating.) Rough calculations of the potential whole-body-averaged SAR under these conditions yield a value close to 1.0 W/kg, although this number remains to be confirmed by dosimetric modeling of seated humans, a technique not yet available. In any case, although the RF exposures of human volunteers often exceeded current safety guidelines, the added heat loads to the body were dissipated easily and with no reported discomfort.

B. Behavioral Effects

Exposure to RF/MW energy can lead to changes in the behavior of humans and laboratory animals. These changes can range from the perceptions of warmth and sound to lethal body temperatures that result in grand mal seizures. Between these two extremes, the trained behavior of laboratory animals can be either perturbed or stopped dead in its tracks. Under certain other conditions, animals will escape and subsequently avoid

RF fields, but they will also work to obtain a burst of RF energy when they are cold.

Over the last 40+ years, studies reporting changes in the behavior of laboratory animals in the presence of RF fields have provided substantial insight into the most probable mechanism of interaction of these fields with intact organisms. This mechanism relates to the generation of heat in the tissues that results in the activation of thermal sensors in the skin and elsewhere in the central nervous system. Studies of human thermal sensation, generated by RF/MW exposures, e.g., Hendler *et al.* [31], Justesen *et al.* [32], and Blick *et al.* [33], reinforce the conclusion that behavioral changes observed in RF exposed animals are thermally motivated. Indeed, measured elevations of surface and deep body temperatures often accompany specific behavioral changes demonstrated in the laboratory setting [34]. The phenomenon of disruption of food-motivated behavior at a whole-body SAR of ~4 W/kg, e.g., de Lorge [35], which has served as the basis for human exposure guidelines since the early 1980s ([30], [36]–[39]), still appears to be a very sensitive and reproducible biological effect of RF/MW exposure. Such behavioral alteration has been demonstrated in a variety of animal species and under many different conditions of RF exposure.

The MW-induced auditory effect, e.g., the ability to perceive certain pulsed RF/MW signals, is an example of another reproducible effect with established thresholds for humans and a number of animal species. For example, Guy *et al.* [40], [41] have shown that a number of human subjects can perceive pulsed 2.45-GHz MW energy as distinct clicks and short pulse trains as chirps or buzzing with a tone that corresponds to the prf of the signal. The threshold for humans at this frequency was consistently found to be about 40 μJ/cm^2 per pulse for pulsewidths ranging from 1 to 32 μs. The SAR per pulse, based on absorption in an equivalent spherical model of the head, was approximately 16 W/kg. The interaction mechanism is the induction of a thermoelastic pressure wave in brain tissue that activates the inner ear receptors [42]. The temperature rise associated with each pulse is of the order of 10^{-5} °C. Although the effect may be annoying, there is no evidence of harm at exposures at or below the peak-power limits found in contemporary safety standards and guidelines such as the IEEE Standard C95.1 [30]. The evoked auditory response is the only confirmed effect at MW frequencies with little temperature rise and dependence on something other than average power density or SAR. Although not behavioral in nature, the effect is, however, one that should carefully be considered as a potential confounder in animal experiments where the subjects are exposed to pulsed RF.

More recently, other behavioral studies have provided evidence for different kinds of behavioral alteration that may not have a thermal basis. A study by D'Andrea *et al.* [43] was conducted after promulgation of the IEEE Standard C95.1-1991, which set limits (100 kV/m peak E-field) on human exposure to high-peak-power, short duration MW pulses (less than 100 ms). Rhesus monkeys were trained on a complex operant task involving color discrimination and were exposed (or sham exposed) for 20 min to two types of 5.62-GHz MW pulses while performing this task. Peak incident power densities studied ranged from 56 to 277 W/cm^2, at a pulse repetition rate of 100 p/s and pulsewidths of 50 ns and 2.8 μs; the average whole-body SAR was 2, 4, or 6 W/kg. Significant alterations in behavioral responses, reaction time, and acquired food pellets occurred during 4 and 6 W/kg exposure, but not at 2 W/kg. Further, high-peak-power pulses and normal radar pulses did not differentially alter behavioral performance, which recovered rapidly after exposure ceased. It is possible that the monkeys could hear the pulses, but the sensation may have been the same for the two types of pulses. Thus, while this study confirmed the earlier behavioral disruption thresholds of 4 W/kg, it did not find evidence of unique high-peak-power MW hazards from fields near the IEEE Standard C95.1-1991 E-field limit.

From the few extant studies that have evaluated "cognitive performance" during or following RF/MW exposure, conclusions cannot easily be drawn. Some performance deficits are observed at a whole-body SAR less than 4 W/kg, while an enhancement of performance has been observed at ~13 W/kg. The cognitive task differences, different exposure systems used, modulation parameters employed, frequency discrepancies between studies, differences in test species, and exposure duration all conspire to make easy interpretation of this sparse literature difficult.

Thus, thermal changes seem to account for most of the reported behavioral effects of absorbed RF energy across the limited frequency range explored. Those studies that report changes in animal behavior during acute RF exposure also involve tissue heating, mild heat stress, and alternate behaviors that are thermoregulatory in nature. Certainly the demonstrated reinforcing and aversive properties of RF energy are derived from tissue heating. As pointed out by Goldman [44], whether low-level RF exposure, which characterizes the chronic studies, also involves tissue heating is unknown, but acclimation would surely ameliorate the impact of such heating in a short time.

C. Nonthermal Effects?

In this era of widespread use of mobile phones and other personal communication devices, there is much speculation over the potential hazard from the low-level radiated fields from such devices (cf. Stewart [45] and Carlo [46]). The hard body of scientific evidence for a thermal basis of RF/MW bioeffects seems to be ignored today in favor of a low-level nonthermal interaction of fields with biological tissues. Certainly, electrocution is a true hazard that can be classified as nonthermal in nature, but is not low level. The recent controversial claims of nonthermal effects, especially RF/MW exposures that are amplitude modulated at ELF frequencies, have neither been substantiated experimentally, nor replicated independently. Many published papers report artifacts, not clean experimental data. One result of the recent International Agency for Research on Cancer (IARC) classification of RF energy as a possible carcinogen is the initiation of several new research programs, especially in the U.K., to search for nonthermal mechanisms of interaction. As noted earlier, there are valid scientific reasons why these programs will fail to bear positive fruit. On the other hand, as Osepchuk and Petersen [47] have noted, millions of people experienced strong RF/MW exposures via clinical diathermy during the last century and with only beneficial consequences.

V. EXPOSURE STANDARDS

A. History

RF/MW safety standards generally refer to regulations, recommendations, and guidelines that specify exposure limits for the purpose of protecting human health. A coordinated effort to develop science-based standards and guidelines began around 1953 when Schwan recommended 10 mW/cm^2 as an exposure limit [48]. This value was based on a simple thermal model that limited the rise in core temperature of an exposed individual to less than 1 °C if about half of the incident energy was absorbed. Further justification of this value was the absence of evidence that opacities in the lens of the eye (cataracts) could be produced at power densities below 100 mW/cm^2. As pointed out by Mumford [48], various organizations adapted the 10-mW/cm^2 value to suit their needs and limits that ranged from about 100 μW/cm^2 to 100 mW/cm^2 were commonly used during the late 1950s. In 1960, the first formal standards project was approved when the American Standards Association [(ASA), which later became the American National Standards Institute (ANSI)] approved the initiation of Radiation Hazards Standards Project C95 and the establishment of a committee charged with developing standards through an open consensus process. The C95 Committee, co-sponsored by the Department of the Navy and the IEEE (then the IRE), published its first standard in 1966 [49]. The recommended limit, then called a "Radiation Protection Guide" was 10 mW/cm^2 across the frequency spectrum from 10 MHz to 100 GHz. Revisions were published in 1974 [50] and 1982 [36]. Each revision was more scientifically sound, albeit more complex than its predecessor. For example, the 1974 standard specifies limits for both the E- and H-fields for frequencies below a few hundred megahertz since by then it was recognized that many exposures in the workplace are in the near field and both field components are important. The 1982 standard was the first frequency-dependent SAR-based standard. In 1989, the C95 committee became the IEEE Standards Coordinating Committee 28 (SCC-28) and the latest standard, the 1999 edition of the IEEE Standard C95.1-1991 [30] was approved for use as an American National Standard by the ANSI in 1992. Unlike the earlier standards, the 1991 IEEE standard contains two tiers over a limited frequency range (between approximately 1 MHz to 3 GHz) based on exposure environment. The recommendations for exposures in uncontrolled environments, e.g., public exposure, is one-fifth the limits for exposures in controlled environments. Some feel that the lower tier is unnecessary and was more of a sociopolitical decision than one based on science—but in an open consensus process, all voices are heard and the majority rules.

SCC-28 is now a committee of the IEEE ICES and is truly an international committee with over 100 members representing over 20 countries. While the role of the main committee is to ensure that the views of the stakeholders are considered, the scientific expertise resides mainly on the subcommittees that develop the standards. The subcommittee that develops the RF/MW exposure limits is larger than the main committee with even wider representation. The 125 members of the subcommittee that developed the latest standard were mostly from academia and the federal research laboratories.

B. Contemporary RF/MW Standards

The most commonly used standards throughout the world are based on the IEEE C95 standards, the recommendations of the National Council on Radiation Protection and Measurements (NCRP), and the guidelines of the International Radiation Protection Association (IRPA) International Commission on Non-Ionizing Radiation Protection (ICNIRP). Both the NCRP and ICNIRP are organizations with established scientific committees that review the literature and make recommendations regarding exposure to RF/MW energy. NCRP is a nonprofit corporation chartered by the U.S. Congress to collect, analyze, develop, and disseminate in the public-interest information and recommendations about: 1) protection against radiation and 2) radiation measurements, quantities, and units, particularly those concerned with radiation protection; ICNIRP evolved from the IRPA INIRC—established in 1977 and chartered as an independent Commission in 1992.

The NCRP is concerned mostly with ionizing radiation, but in the mid-1970s, Scientific Committee 53 (SC-53–now SC-89-5) was established to review the scientific literature and recommend limits for exposure to RF/MW energy. SC-53 consisted of six members, five advisory members, and five consultants—eight of whom were also members of the ANSI C95 committee at the time. In 1986, the SC-53 literature review was published with recommendations of the NCRP Report 86 [37]. Although the recommendations were based on the 1982 ANSI C95 exposure limits, a major departure was the incorporation of an additional safety factor of five for exposure of the public, i.e., a lower tier. Even though the consensus of the committee was that all evidence indicated that confirmed effects related to RF/MW exposure are threshold effects, with established thresholds well above the limits for occupational exposure, the stated rationale for the lower tier was based on the premise that the public would generally be exposed for longer exposure durations than the worker.

The most recent ICNIRP guidelines were approved in November 1997 and published in 1998 [38]. At the time the guidelines were developed, the Commission included the participation of 17 scientists and 11 external experts from 12 different countries, including Sweden, Australia, U.K., Germany, Poland, and the U.S. Although the ICNIRP field limits in part of the RF/MW region differ from those of the IEEE and NCRP, the standards and recommendations of all three organizations are based on the same biological endpoint and whole-body-averaged SAR threshold value, i.e., behavioral disruption of food-motivated behavior and 4 W/kg, respectively. Any differences between the exposure field limits at RF/MW frequencies are related to engineering interpretations and mostly differences in the applied safety factors—not disagreements on the biology.

C. Rationale

RF/MW safety standards are based on the results of critical evaluations and interpretations of the relevant scientific research—ideally, all laboratory and epidemiology research that relates any biological response, from short- and long-term exposure, would be included. From this evaluation, a threshold SAR is established for the most sensitive confirmed response that could be considered harmful to humans regardless of the nature of the interaction mechanism. To account for uncertainties in the data and to increase confidence that the limits are well below the levels at which adverse[2] effects could occur, the resulting threshold is lowered by a somewhat arbitrary safety factor, usually 10–50 times below the observed threshold (at least for the IEEE standards and the NCRP recommendations—others have much larger safety factors). The threshold SAR is sometimes called a "basic restriction". In the case of the IEEE standard, threshold SAR is presented as an exclusion, i.e., the incident field limits can be exceeded provided the SAR limits are not. The MPEs derived from the threshold SAR—i.e., exposure field and induced current limits—sometimes called "investigation levels" or "reference levels"—ensure that the resulting SAR and induced current densities are below the corresponding thresholds under all circumstances of exposure. In the absence of any convincing evidence for long-term effects at low levels, modern RF/MW safety standards and guidelines are based on short-term studies. While cancer is a major consideration in assessing risk from long-term low-level exposures, the weight of the evidence does not support the idea that RF energy can cause cancer in animals or humans or change cells the way that known carcinogens do.

The scientific literature shows that at sufficiently high levels, adverse effects can occur from RF exposure. Laboratory studies have shown a continuum of effects from increases in temperature at sufficiently high exposure levels, and the concurrent accompanying physiological changes, to the disruption of learned behavioral tasks, at moderate exposure levels. At lower exposures, there is no convincing evidence that effects deemed adverse occur, but sensitive studies can detect adaptive responses, such as increased sweating, or decreased metabolic rate. These responses have been observed in numerous studies in several species and exposure levels, and other research and other knowledge about physiology confirm the relevance of these observations for humans. As indicated above, reported effects at even lower exposure levels, sometimes called "nonthermal" effects, have not been confirmed (other than the "auditory" effect if that is considered "nonthermal," which is an arcane point).

Studies in laboratory animals at various frequencies help to identify dose–response patterns and thresholds. The most sensitive and reliable confirmed biological response that could be considered potentially harmful to humans has been found to be the disruption of food-motivated learned behavior. Since this effect is modest and represents an adaptive response, it serves to identify a threshold for potentially harmful effects. The threshold for behavioral disruption, in terms of whole-body-averaged SAR, has consistently been found to lie between approximately 2–9 W/kg across animal species, from rats through several species of monkeys, and frequency, from approximately 200 MHz to over 5 GHz. Associated with this threshold is an increase in body temperature, usually of approximately 1 °C. The IEEE, NCRP, and ICNIRP RF/MW exposure standards and guidelines are each based on behavioral disruption and a threshold SAR of 4 W/kg across the range of frequencies where SAR is the valid dosimetric parameter, i.e., from approximately 100 kHz to 6–10 GHz. A safety factor of ten is incorporated for exposure in controlled environments, e.g., the workplace, and an additional factor of five for exposure in uncontrolled environments. Thus, the basis for contemporary RF/MW safety standards a maximum whole-body-average SAR of 0.4 and 0.08 W/kg for exposures in controlled and uncontrolled environments, respectively. Subtle differences in the derived limits developed by different organizations are associated with the underlying engineering assumptions used to derive the MPEs, or differences in philosophy of determining safety factors—i.e., safety margins (note that the absence of safety margin implies existence of EM sensitive people)—not with any specific biological response or its threshold.

The SAR distributions resulting from exposure to RF/MW energy are complex. When the 1982 ANSI C95 Standard was developed, it was noted that many animal exposures are carried out under far-field irradiation conditions. Dosimetric studies at the time revealed that, under such conditions, the peak-to-average value of the SAR distribution in laboratory animals was typically 20 : 1. This 20 : 1 ratio was used to develop peak spatial-average SAR limits for exposures of small portions of the body, e.g., from a wireless handset. Thus, the peak-spatial average SAR limits of the 1991 IEEE C95.1 Standard for exposures in controlled and uncontrolled environments is 8 and 1.6 W/kg, respectively, averaged over a rather arbitrary mass of 1 g of tissue in the shape of a cube [30]. The somewhat less arbitrary ICNIRP peak spatial-average SAR limits are based on effects to the eye. Specifically, the threshold associated with the induction of lens opacities in the eyes of rabbits has been shown to be greater than 100 W/kg. The mass of the eye is approximately 10 g—by incorporating safety factors of 10 and 50 times, the resulting ICNIRP peak spatial-average values are 10 and 2 W/kg averaged over any 10 g of contiguous tissue for occupational and exposure of the public, respectively.

Below 100 kHz, the IEEE SCC-28 is working on improved transitions to the rules based on electrostimulation, which will match a new standard being developed for frequencies below 3 kHz. Above 6 GHz, substantial liaison with the laser standards community in recent years has assured a scientifically defensible transition from the principal MW range below 6 GHz to a standard based on surface absorption assessment that matches laser standards at 300 GHz.

D. IEEE Process

Guidelines and recommendations developed by the ICNIRP and NCRP committees is an informal and somewhat nontransparent process, whereas the IEEE process is open and transparent. Moreover, throughout their history, the C95 committees (and now IEEE/ICES SCC-28) have been by far the most innovative and had the greatest influence on RF/MW safety stan-

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[2] An *adverse* biological response is considered any biochemical change, functional impairment, or pathological lesion that could impair performance and reduce the ability of an organism to respond to additional challenge. *Adverse* biological responses should be distinguished from biological *responses* in general, which could be adaptive or compensatory, harmful, or beneficial.

dards worldwide [51]. For these reasons the IEEE process will be described briefly.

The process begins at the subcommittee level (which is open to anyone with an interest) with the identification by the Literature Surveillance Working Group of reliable studies reporting biological responses—from reversible effects and responses of adaptation to irreversible and biologically harmful effects. (The Literature Surveillance Working Group has identified over 1500 relevant citations from a number of databases and inputs from federal agencies and other organizations that are regularly polled.) Selected papers undergo a comprehensive engineering review by two randomly selected reviewers from the Engineering Evaluation Working Group and by two randomly selected reviewers from one of the appropriate biological evaluation working groups, e.g., *in vivo*, *in vitro*, and epidemiology. The reviewers are subject matter experts—many of whom are not members of the subcommittee or the IEEE. Theoretical papers, e.g., papers that speculate on various mechanisms of interaction, are reviewed separately and judgments made as to their relevance for standard setting.

The literature evaluation has now been computerized in order to expedite the process of handling large amounts of data (several thousand evaluations) and to allow the Risk Assessment Working Group to search for key evaluations. The Risk Assessment Working Group evaluates the implied risk for human beings and defines a threshold SAR for which potentially deleterious effects are likely to occur. During the review process, several concerns that have been raised regarding the 1999 edition of IEEE Standard C95.1-1991 are now being addressed including a more appropriate averaging time at the higher MW and millimeter-wave frequencies, reexamination of the basis and need for two tiers, reexamination of the basis for the magnitude of the spatial peak SAR limits and the corresponding averaging volume, development of a scientific basis for the averaging time at frequencies below 100 kHz and for induced current and contact current, and development of a scientific basis to protect against spark discharges.

Draft standards developed by the subcommittees are subjected to a rigid, but open, balloting process before they are moved to the main committee for approval. Approval requires a letter ballot with at least 75% of all ballots returned. Attempts must be made to reconcile every negative ballot and all unreconciled negative ballots must be circulated, with a rebuttal, to offer all voting members an opportunity to comment, affirm, or change their vote. If, after all unreconciled disapprovals have been circulated, 75% of the initial number of returned ballots remain affirmative, the process is repeated at the main committee level—usually by the IEEE Balloting Center. The requirements for approval at the main committee level are the same as those at the subcommittee level. The main committee is comprised of the stakeholders that have to apply the standard. Once approved by the main committee, the draft is submitted to the IEEE Standards Board. The IEEE Standards Board has oversight to ensure that due process has been followed, e.g., all negative ballots and appeals have been addressed and coordination has taken place. At the time of approval by the IEEE Standards Board, the document becomes an IEEE standard and, after public review, an approved ANSI American National Standard, provided all comments from the public are addressed.

ICES is now international and influence of the C95 standards is now global in scope. Through the World Health Organization's standards harmonization effort, ICES is working closely with other expert groups, e.g., ICNIRP, toward the development a single science-based global standard.

VI. WHAT MAY THE FUTURE HOLD?

The proposal by Pound [52] that MWs be used for the comfort heating of humans, conceived in the aftermath of the mid-1970s energy crisis, may not be realized for decades because of continuing concern for the potential "hazards" attending such exposure. However, RF/MW heating for cancer therapy, for rapid rewarming of hypothermia victims, and for incubation of newborn mammals is being vigorously explored on many research fronts. Given a frequency that will allow maximal penetration of the energy well below the surface of a given organism, rapid heating of the body can be accomplished far more efficiently with RF/MW energy than with radiant or convective heat sources. Buffler [53] described the standard practice of immersing a hypothermic newborn lamb for hours in a water bath as tedious and marginally successful. Furthermore, prolonged soaking removes the animal's scent so that the mother rejects it afterward. Heated shelters for sheep are expensive and, therefore, little used. Instead, Buffler proposed rewarming the lamb rapidly with RF/MW energy to enhance its survival and ensure its acceptance by the mother.

Morrison *et al.* [54] have successfully incubated flocks of chicks with MWs on a demand basis, beginning on the seventh day of life (in a cool environment—16 °C). Either 2450-MHz MW or infrared (IR) heat was provided when a chick pecked at a wall panel. The birds used both sources of thermal energy efficiently for periods as long as 22 days. No difference in growth rate between IR- and MW-heated chicks were evident, nor were any detriments in health or overall behavior measured in the MW-exposed birds.

The potential for MW incubation of newborn rats has been explored, with emphasis on changes that may occur in thermoregulatory ability when immature rats are repeatedly exposed to MW fields. This research determined the optimal conditions (SAR and T_a) for the incubation of rats from 2 to 16 days of age (Spiers and Adair [55], Spiers *et al.* [56]). After this incubation, the exposed animals were allowed to grow to maturity, mate, and produce young, while being tested for a variety of biological endpoints. No hazardous consequences of acute or repeated exposure to MW fields at low SAR were found when the animals were incubated under optimal exposure conditions. It is only a short step, then, to the consideration of a MW incubation system for premature human infants, who are so susceptible to the dehydrating and burning characteristics of conventional convective and radiant incubators in use today.

Profoundly hypothermic anesthetized rhesus monkeys have been successfully rewarmed to normal body temperature by RF/MW radiation treatment with an induction coil by Olsen and David [57] and Olsen *et al.* [58]. Deep body temperature as low as 20 °C, the point of cardiovascular collapse, were returned to normal within 2 h and no deleterious aftereffects were observed over a period of nine months. The goal of this research with nonhuman primates was the development of a RF/MW resuscitation system for hypothermic humans, a goal achieved by Hesslink *et al.* [59]. Apart from the necessity of controlling for the dose rate and the skin temperature, there seems little doubt that this method of rewarming can have great utility in the future.

Pound's original idea of comfort heating of human beings with electromagnetic energy [52] has yet to be brought to fruition, principally because of the persistence of electrophobia in the general population. Apart from saving energy (100 W of RF energy at 3.0 GHz will warm a lightly clothed individual in a 50 °C environment), such a system will produce a state of thermal comfort, can be instant-on-and-off in each room, and can be tailored to the number of occupants of the space. Those of us who measure human responses to diverse RF/MW fields are confident that this electromagnetic energy will play a large role in the thermal control of personal environments in the future, whether in the home or in a space capsule

VII. CONCLUSIONS

The study of the biological effects of RF energy is a mature scientific discipline with over a 50 year history and a literature database that is extensive, but of uneven quality. Scientists have been developing RF safety criteria based on critical evaluations and interpretations of the scientific literature for almost 50 years. Despite many thousands of studies that have been reported on all aspects of the subject since the first safety criteria were proposed, the exposure limits have not changed significantly. Significant changes to the exposure limits that have occurred over the years have mainly resulted from a better understanding of the dosimetry. Even though the field limits developed by different organizations may differ slightly, there is agreement on the fundamental bases for RF safety standards/recommendations. The important organizations, such as ICNIRP and ICES, are now working together in an effort toward harmonization. Uniform RF/MW exposure standards worldwide is one step forward toward mitigating many traditional concerns—e.g., the science is inconclusive, all radiation is hazardous and should be avoided (no level of exposure is safe), artificial sources of anything are more dangerous than natural sources—and opening the door for the acceptance of innovative and beneficial technologies.

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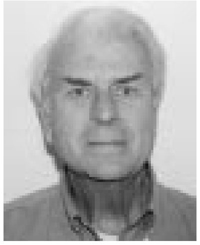

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